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16. Abstract

The mechanism of the high-temperature Ar arc is interpreted in those essential points in which it deviates from the known arcs based on earlier measurements and experiments. The following points are discussed individually: the charge carrier balance, the energy balance, the volt-amp characteristics, and the difference between high-temperature arcs in Ar and N. Besides the volt-amp characteristic of a 10 mm long arc in Ar between 10 and 200 amp, the anode fall, cathode fall, and arc gradient were obtained with the aid of probes. The difference between Ar and N arcs are attributed to variations of the heat conditions and electrical conditions at different temperatures of the gas.

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THE DISCHARGE MECHANISM OF THE HIGH-TEMPERATURE ARC*

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In three earlier publications [2, 3, 4]*** we had described /655** high-temperature arcs in argon and nitrogen and also were able to explain partly their properties, insofar as they differ from those of ordinary arcs. In particular, a purely thermal ionization was proven there even in the cathode fall range. The low arc voltage fall found to 8 V follows, according to our explanation, from this thermal ionization and from the maximum plasma conductivity existing in a wide column range. Both effects are, for their part, a consequence of the high column temperature. Moreover, it was possible to explain the anode mechanism and therefore the dependence of the anode fall on the current intensity, arc length, and contraction, as well as the effect of the plasma beam on the anode mechanism. But to understand fully the arc mechanism, a number of questions still remained open, which will be treated qualitatively below. We refer here to: 1. the carrier balance, 2. the energy balance, 3. the variation of the volt-ampere characteristic, 4. the difference between argon and nitrogen column.

These problems now will be treated one after the other. Here we will refer mainly to the argon arc, since it could be studied better because of its very stable combustion than the /656 nitrogen arc which is very similar in its behavior but less stable. Section 4 will discuss the differences between the two arcs.

*Dedicated to Professor Dr. H. Rau with hearty greetings on his seventy-fifth birthday.

**Numbers in the margin indicate pagination in the foreign text.

***Hereafter designated by I, II and III.

1. The Carrier Balance

The ordinary idea of discharge plasmas, in which in both fall regions carriers are produced and reach the opposite electrode in thermal drift movement, is not applicable to our high-temperature arcs, because, as was shown in III on the basis of energy measurements, a strong plasma flow exists from the cathode end of the arc in the direction towards the anode. Since in this region the plasma is almost totally ionized, this plasma flow can carry only ions and electrons. This means that besides the ordinary and in this case very weak drift in the field, a strong ionic flow opposite to it is superimposed on the thermal ion movement.

Thus the current equations are:

$$j_e = n_e b_e \mathfrak{E} + eD_e \operatorname{deg} n_e + n_e v_{st}$$
$$j_i = n_i b_i \mathfrak{E} - eD_i \operatorname{deg} n_i - n_i v_{st},$$

where v_{st} is the flow velocity of the plasma beam.

The total current consists of two components, while only the resulting ion current does not reinforce as usual, but weakens the electron beam.

The axial diffusion flows are relatively small, since n_i and n_e hardly change in the argon arc in the axial direction, and practically do not change at all for the nitrogen arc. Nevertheless it is noteworthy that for argon in a temperature range above 18,000°K, n_e decreases again slightly with increasing temperature (compare I, Fig. 7). Here, therefore, the electron diffusion current must take place in the direction of increasing temperature, that is, in the regions close to the cathode, the direction towards the cathode. But this effect would hardly have a practical importance with the strong plasma flow in the opposite direction.

Because of the plasma beam now the ions which flow towards the cathode in low current discharges and are produced in the anode fall [5, 6] are produced in the cathode fall or at the cathode end of the column. Therefore there must be a more or less extensive ionization zone from which the positive ions flow on the column side towards the anode, and on the cathode side towards the cathode. The latter follows in the first place from the fact that the plasma beam forms only at a finite distance in front of the cathode and the drift is still effective in the intermediate layer. Secondly, a certain ion flow must be sent to the cathode for energy balance reasons, for its heating. In this ionization region, in which the plasma /657 beam is also formed, therefore, contrary to low current arcs free from plasma beams, all ions of the arc must be produced. The fact that this ionization takes place thermally is shown by the variation of the field intensity which reaches on a free path length only the 10^{-3}th part of the ionization voltage. The electrons needed in front of the cathode are supplied by the cathode by collaboration of thermal and field emission [1] and accelerated in the cathode fall to the velocity of about 3-4 V corresponding to the high column temperature. This initially directed velocity is converted quickly by many collisions into a thermal velocity, while a Maxwell distribution arises, in which a sufficient number of energy rich particles occur ("Maxwell tail") to allow the substitution of the outflowing ions by thermal ionization. In the column now all particles flow toward the anode, the ions with velocity v_{st} (since b_i is very small), the electrons with $v_{st} + b_e \mathfrak{E}$. Along the axis the degree of ionization decreases somewhat towards the anode in the noncylindrical arc. Nevertheless, a very considerable portion of positive ions come in front of the anode. Here the plasma temperature drops in a very narrow range from about 18,000°K to the temperature of the cooled anode. In this region the ions must be destroyed, insofar as they do not flow out laterally. Thus near the anode a strong recombination and reduction of conductivity occur. Whether these two processes still arise in the

thermal equilibrium cannot be indicated with certainty for the very high temperature gradient in the thin layer. Since in anodically uncontracted arcs the current density directly before the anode does not differ considerably from the subsequent column, the current transport requires, because of the lower conductivity immediately before the anode, an increased field intensity here as compared with the column. Summed up, this gives the measured anode fall. It may also be stated that the anode fall voltage must draw the current through the poorly conductive layer. Between plasma and anode lies a clearly visible dark space about 0.1 mm thick. It was observed that this dark area is the more extensive in the axial direction, the lower the plasma temperature. Therefore the dark space extends in the axial direction only with extension of the arc, secondly with reduction of the current intensity, thirdly at a large lateral distance from the arc axis. Figure 1 shows the anodic extension for 2 and 6 mm arc lengths. We believe that through this effect the rounded arc extension of the uncontracted arc arises on the anode. But when this dark space indicates a zone of poor conductivity, which requires an increase of voltage, that is, an anode fall; the latter must be the greater, the more extensive the dark area. Consequently, in the case of the argon arc, for which the extension of the dark space increases con- /658 tinuously with increasing arc length, the anode fall must also increase, even when the current intensity is large enough to wash practically all the ions to the anode through the plasma flow, so that the effect of increasing ion loss in front of the cathode described in III does not play any part in the arc extension by normal drift. In the nitrogen arc with its isotherms running almost parallel in the column, according to expectation, no change was observed either of the dark area or anode fall in variations of the arc length. The neutral particles, which arise in front of the anode in recombination, are deflected sideways.

2. Energy Balance

In III it was measured that the energy converted in the

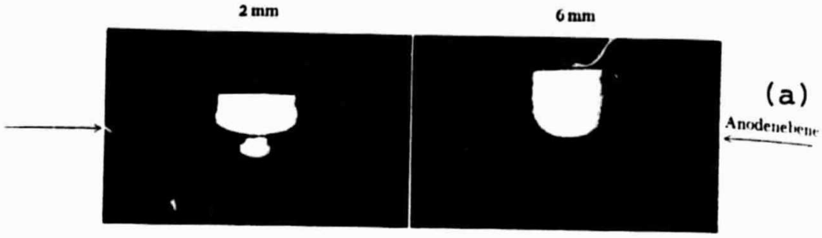

Fig. 1. Anodic extension of the argon high-temperature arc of 200 A and 2 and 6 mm length. The upper arc portion is cut off. The bright spot under the anode plane is a reflection. The illumination times are adjusted in such a way that in both photographs approximately the same degree of blackening is achieved.

Key: (a) Anode plane.

column and in the anode fall is transported totally to the anode, except for slight radiation losses. Since the energy required for cathode emission is recovered in the neutralization of the electrodes on the anode, the cathode fall energy is used essentially for heating the electrons emitted by the cathode to a temperature of approximately 30,000°K. Since the cathode fall is somewhat of the order of magnitude of this electron temperature, no noticeable amount of energy can be removed by cathode cooling. This conclusion was confirmed by measurements. The decisive question for the entire mechanism of the high-temperature arc is, however, that of the origin of the much higher temperature of the column as compared with other arcs, particularly in its cathode part. The answer must follow from a complete energy balance of the column, but its establishment and calculation fails practically because of the large number of the interacting individual processes and the many unknown data. But some qualitative statements may still be made. The current transport requires a high conductivity and this again requires a relatively high temperature as compared with ordinary low-current arcs, even though not at the level actually measured in front of the cathode. Whereas for /659
most low-current arcs with degrees of ionization of 1 to several percent, a considerable portion of the ions come from atoms or molecules of low ionization voltage (C and NO in the carbon arc, metals in many other arcs), a relatively low temperature is

sufficient for their thermal ionization, in the practically 100% ionization of the high-temperature arcs, all ions come from atoms or molecules of the carrier gases with their relatively high ionization voltage. Another point arises in front of the cathode: the experimental conditions (point-shaped cathode tip and cooling from the top by gas flow) make a high current density compulsory in the cathode side column section (cathode stabilization according to Weizel), and therefore for constant electrical conductivity no longer increasing with temperature above 16,000°K a correspondingly high field intensity in front of the cathode, finally, as a result of high $j \cdot \mathfrak{E}$, a high power conversion, which should give in the stationary equilibrium with the energy removal determined by the radial heat conduction (according to $k(T)$) precisely the measured high temperatures in the column part on the cathode side.

3. Characteristic

In Fig. 2 the characteristic of a 10-mm long argon arc is shown between 10 and 200 A. Moreover, the variation measured with probes of the anode fall U_A, cathode fall U_K and column voltage U_S are plotted. It is apparent that we can differentiate two ranges of current intensity: the low current range below about 50 A, in which the fall of the entire arc voltage is determined with increasing current intensity by the decrease of the cathode fall U_K, while column voltage and anode fall remain constant, and the high current range above 50 A, in which the weak decrease of the electrode falls is overcompensated by a stronger increase of the column voltage U_S and the characteristic increases slightly. These two regions are not separated sharply from each other. The transition takes place gradually between 30 and 60 A. Now the variation of the three components will be discussed in the low and high current ranges.

a) Low current range. U_K decreases with increasing current intensity. The cathodic current density increasing with the

current intensity and temperature in front of the cathode causes an increased heating of the cathode, so that a lower suction voltage is needed for the electron emission of the cathode. U_K decreases consequently with increasing current intensity I, until the emission takes place purely thermally and the cathode fall is only needed now to accelerate the electrons emitted to the velocity of the column temperature. The fact that the anode does not vary much with I is based on the anodic contraction. In III it was described in detail that the low voltage arc contracts so strongly on the anode that an anode current density independent of the current intensity is adjusted, which for its part causes a constant anode drop. The column voltage U_S also does not vary with the current intensity in the region below 50 A. It was known for the first time from measurements that the column temperature to below 6 A lies above 16,000°K for a column channel of about 3 mm diameter. This means that in the mean discharge region, the conductivity depends little on the temperature (I, Fig. 11). Moreover it was established by the comparison of blackening of photographs that the arc radius increases with $\sqrt{I}$, that is, a constant current density is adjusted. Therefore $\mathfrak{E}$ and U_S must be constant. The reason for the variation of the arc radius with $\sqrt{I}$ must once again be sought in the energy balance. In this case the consideration of the column alone would be sufficient, if it is assumed that the current density is adjusted in such a way that the minimum principle of Steenbeck is satisfied. But we will see below for the high current region that this explanation is insufficient without referring to the electrode regions.

b) High current region. The cathode fall U_K first falls slowly above 50 A and later remains constant. The purely thermal emission seems to have been reached at about 100 A. Above 150 A a very weak increase takes place. The current density and temperature increase somewhat in front of the cathode (j approximately 20%, measured by comparing the blackening of photographs) /661

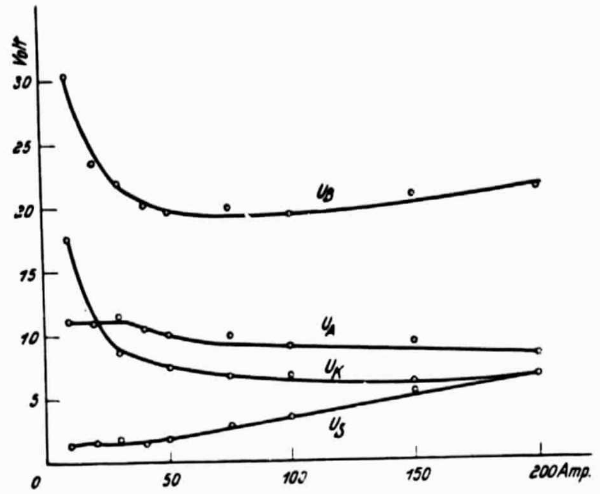

Fig. 2. Dependence of the total arc voltage U_B, the cathode fall U_K, the anode fall U_A and the column voltage U_S on the current intensity of a 10-mm long argon arc.

and therefore also the voltage required to accelerate the electrons, and specifically by 0.2-0.5 V. But this change is insignificant for the variation of the characteristic.

The anode fall U_A decreases with increasing current intensity above 50 A for an anodically noncontracted arc, which was attributed in III and Paragraph 1 of this article to the effect of the plasma beam and the conductivity increasing with I in front of the anode.

The column voltage U_S increases in the high current region with increasing current intensity. Here most of the increase in the field intensity takes place in the regions near the cathode. Thus, for example, in the transition from 100 to 200 A at a distance of 1.5 mm in front of the cathode, an increase of field intensity was measured from 16 to 30 V/cm, while the field intensity increases 6 mm in front of the cathode only from 1.5 to 1.8 V/cm and no longer varies for an even greater distance. Since σ here too is practically independent of the temperature, the current density must increase with increasing field intensity, and it was possible to confirm this optically. j increases by approximately 20% in front of the anode, but about 50% in front of the cathode, that is, at the cathode end of the fully formed column. The reason that for higher current intensity a current density is adjusted requiring a higher field intensity must now lie in the behavior of the fall regions, especially the cathode fall and the ionization zone, from which the plasma and plasma beam

are formed, but cannot be calculated quantitatively.

4. Comparison of Argon and Nitrogen High-Temperature Arcs

So far we have only discussed the argon arc, but most of the phenomena discussed were also observed in arcs of the same type in nitrogen. A surprising difference in the form of the phenomenon is the formation of an almost cylindrical core in the nitrogen arc, which appears therefore just like a high current carbon arc column, although temperature, degree of ionization, voltage and radiation deviate only little from the corresponding data of the argon arc. King [7] had already indicated that the core formation must be related to the temperature variation of thermal conduction. Figure 3 shows the thermal conductivities of both gases as a function of the temperature. For argon the classical thermal conduction was calculated up to nearly 12,000°K, for high temperatures, it was small as compared with thermal conduction of electrons, which was calculated according to the method of Spitzer [8]. Moreover, the ionization component of the thermal conduction was taken into consideration, although it is smaller by three orders of magnitude and therefore does not play a noticeable role.

Since the degree of ionization is higher for higher temperatures than for low ones, ions diffuse constantly in the concentration gradient into the colder and neutral atoms in the hotter arc regions. The ions transport their ionization energy obtained in the hot area to a colder zone and give it off here for recombination. Thus a certain portion of energy is removed constantly from the hotter zones. The same process occurs for molecular gases in a low temperature range in dissociation processes. /662

The thermal conductivity curve for nitrogen was made available to us by Mr. Burhorn. Here the dissociation component of the thermal conduction, which is superimposed between 5000° and 10,000°K on the classical thermal conduction, appears very

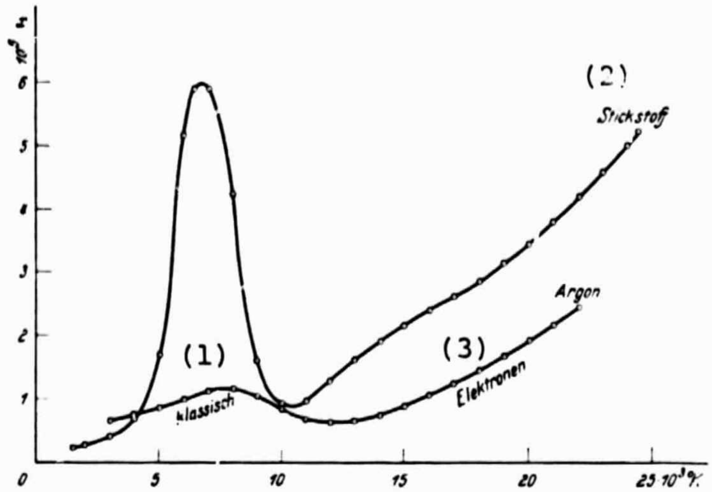

Fig. 3. Dependence of the thermal conductivity on the temperature for argon and nitrogen.

Key: 1. Classical
2. Nitrogen
3. Electrons

clearly. Thus a marked minimum occurs at 10,000°K. A low thermal conductivity implies, however, a large temperature gradient and therefore a significant variation of radiation. Since this variation is limited to a very narrow temperature range, we see as contrast effect the external edge of the arc core. Therefore, the latter must be at about 10,000°K. Unfortunately for the nitrogen arc, besides a determination of the 16,000° isotherms, no exact measurements were possible, the interpolation of the radial temperature degrees from the measurement point at 16,000°K through an assumed core boundary of 10,000°K to 5000°K on the visible arc edge led however to a very possible curve. The electrical conductivity of nitrogen does not increase much any longer at 16,000°K, contrary to argon, in which the minimum has already been reached at 12,000°K. This implies a preference of somewhat higher temperatures, which could also be confirmed in the cathode region by measurements. For the rest, the above-given considerations could be applied basically also to /663
the nitrogen high-temperature arc. A different behavior of the anode fall caused by the arc core was already discussed in III.

The mechanism of free burning high-temperature arcs is thus understandable qualitatively in its main points. Some of these considerations could be confirmed at higher pressures by investigations on high-temperature arcs; a report will shortly be given about this.

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